Relationship Between Sugarcane Rust Severity and Soil Properties In Louisiana

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ABSTRACT

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The extent of spatial and temporal variability of sugarcane rust (*Puccinia melanocephala*) infestation was related to variation in soil properties in five commercial fields of sugarcane (interspecific hybrids of *Saccharum* spp., cv. LCP 85-384) in southern Louisiana. Sugarcane fields were grid-soil sampled at several intensities and rust ratings were collected at each point over 6 to 7 weeks. Soil properties exhibited significant variability (coefficients of variation = 9 to 70.1%) and were spatially correlated in 39 of 40 cases with a range of spatial correlation varying from 39 to 201 m. Rust ratings were spatially correlated in 32 of 33 cases, with a range varying from 29 to 241 m. Rust ratings were correlated with several soil properties, most notably soil phosphorus (r = 0.40 to 0.81) and soil sulfur (r = 0.36 to 0.68). Multiple linear regression analysis resulted in coefficients of determination that ranged from 0.22 to 0.73, and discriminant analysis further improved the overall predictive ability of rust models. Finally, contour plots of soil properties and rust levels clearly suggested a link between these two parameters. These combined data suggest that sugarcane growers that apply fertilizer in excess of plant requirements will increase the incidence and severity of rust infestations in their fields.

Additional keywords: fertility levels, spatial variability.

Brown rust of sugarcane (interspecific hybrids of *Saccharum*), caused by *Puccinia melanocephala* Syd. & P. Syd., first was observed in the continental United States, including Louisiana, in 1979 (6,13). In Louisiana, the disease was considered to be of minor importance until 2000, when an epidemic occurred throughout the sugarcane industry (9). The outbreak was of concern to the sugarcane growers of Louisiana because the most severely affected cultivar was LCP 85-384, a cultivar that was becoming increasingly popular with growers since its release in 1993. By 2000, LCP 85-384 occupied ≈71% of the sugarcane production area in Louisiana, and by 2004, it occupied 91% of the area (16). Although the rust epidemic was not as severe during the 2 years following the 2000 growing season, the incidence and severity of rust again increased during the most recent 3 years (8).

A number of factors affect the incidence and severity of rust in sugarcane, including cultivar susceptibility, pathogen genetics, plant growth stage, weather conditions, plant nutrition, and soil characteristics (1–3,18). From the time cv. LCP 85-384 was released until 2000, it was considered to be resistant to rust (9). Although the rust outbreak of 2000 in LCP 85-384 suggested a genetic change in the pathogen or selection pressure favoring the emergence of a more virulent variant within the pathogen population, this hypothesis has not been demonstrated experimentally (9). Races of *P. melanocephala* have been demonstrated in Florida and India (5,21,22).

In a study of the relationship of leaf nutrient status and rust severity, it was concluded that the relationship was complex, but that rust severity appeared to be associated with imbalanced plant nutrition (2). The association of soil nutrient characteristics and severity of sugarcane rust was investigated at seven locations in Florida (3). It was found that rust severity was negatively correlated with soil pH at all sites (i.e., rust decreased with increasing pH); however, they concluded that it was not the sole determinant affecting rust severity. Among the soil nutrients tested, phosphorrus was the one most consistently correlated with rust severity, a higher level of soil phosphorus being associated with higher rust severity.

Initial infections of rust within Louisiana sugarcane fields often are observed to develop in varying patterns within a field, and initially affected areas appear to remain the most severely affected areas of the field. It also has been observed recently that variable patterns of rust infection frequently occur in areas that have been precision land-leveled, with higher levels occurring in parts of the field that received additional soil. Soil samples taken from areas where soil was removed and where soil was deposited (filled) revealed an interesting trend. Soil organic matter (OM), phosphorus, sulfur, and potassium frequently appear at higher levels in filled areas, whereas magnesium is often lower (M. P. Grisham and R. M. Johnson, *unpublished*). Soil pH has been observed to vary in both directions. Changes in these soil properties would have a direct affect on soil chemistry and fertility and could have a significant influence on plant growth, which in turn may influence rust infestation. This study was undertaken to determine whether differences in soil properties are, in fact, associated with these in-field variations in rust initiation and severity.

MATERIALS AND METHODS

Sampling information and soil classification. Rust mapping experiments were conducted at two sites on Golden Ranch Plantation in Gheens, LA and on Peltier Farms and Acadia and Rebecca Plantations in Schriever, LA. All sites were "plant-cane" (first-year crops) of sugarcane cv. LCP 85-384. At each site, a

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handheld computer (Compaq IPAQ; Hewlett Packard, Palo Alto, CA) equipped with a global positioning system (Navman, Raleigh, NC) and mapping software (Site Mate; Farmworks Software, Hamilton, IN) was used to determine site boundaries, total plot area, and grid-sampling points. The sites at Golden Ranch Plantation were 8.9 and 6.0 ha in size and were sampled on 0.4- and 0.2-ha grids, resulting in 23 and 27 samples per site, respectively. Both sites were composed of both Cancienne silt loam and silty clay loam soils (fine-silty, mixed, superactive, nonacid, hyperthermic Fluvaquentic Epiaquepts). The site at Rebecca plantation was 4.1 ha in size and was mapped on a 0.2-ha grid, resulting in 20 samples. The site was mapped as a combination of Gramercy and Gramercy-Cancienne silty clay loam soils (fine, smectitic, hyperthermic, Chromic Epiaquerts). The last two sites were smaller fields that were mapped using a finer mesh grid to determine whether spatial correlation was present at smaller scales. The first site on Acadia Plantation was 2.2 ha in size and was mapped on a 0.04-ha grid, resulting in 53 samples. The site was composed of Cancienne silt loam and silty clay loam soils as well as Schriever clay (very-fine, smectitic, hyperthermic Chromic Epiaquerts). Finally, the site at Peltier Farms was 0.7 ha in size and was mapped on a 0.02-ha grid, resulting in 37 samples. The site was composed of Cancienne silt loam and silty clay loam soils. It should be noted that this site had been out of sugarcane production for 2 to 3 years prior to the crop that was rated.

Soil analysis. Soil samples (0 to 20 cm) were collected from each grid point at all locations during the first rust-rating period. Samples were air dried, ground with an electric grinding mill (Straub 4E; QCG Systems, Phoenixville, PA), and analyzed (A&L Analytical Laboratories Inc., Memphis, TN). Soil properties determined included soil OM, soil pH, soil buffer pH, exchangeable cations (Ca, Mg, and K), soil cation exchange capacity (CEC), soil phosphorus, and soil sulfur. Phosphorus and major cations present in soil samples were estimated using the Mehlich 3 extraction procedure (15) and inductively coupled plasma-atomic emission spectrophotometry (U.S. Environmental Protection Agency method 200.7 [14]), respectively. Soil OM was determined by Walkley-Black oxidation (17). Soil pH was determined in a 1:1 soil/water suspension, and soil buffer pH using the Shoemaker, McLean, and Pratt buffer (23). The soil CED was calculated by summing exchangeable cations. Soil fertility levels were based on A&L Laboratory recommendations for sugarcane grown in Louisiana.

Rust ratings. Ratings were collected at weekly intervals from 18 May 2005 until 16 July 2005. The severity of rust infestation was visually rated on a scale from 0 to 9 based on a published rust rating scale (4) by three independent observers. Rust rating was based on 0 = no symptoms; 1 = yellow flecks; 3 = few pustules; 5 = moderate number of pustules, slight premature necrosis of lower leaves; 7 = numerous pustules, death of lower leaves; and 9 = numerous pustules, extensive leaf necrosis. Estimates were made in the area immediately surrounding each grid point for all locations. An average of the three ratings is reported.

Statistical analysis. Exploratory and descriptive analyses of rust and soil data were performed by first calculating univariate statistics with PROC UNIVARIATE (20). Spatial correlations in the rust or soil data were summarized using variograms. The variogram measured the average dissimilarity between data points separated by a given distance (7). The graphical variogram provided a summary of measured spatial structure of a given property within the experimental location. The experimental variogram, which is computed from the data, usually is described or 'fit' to a theoretical variogram model (12). One important feature of the variogram is the range, which is the maximum distance at which spatial correlation is observed. A small value for the range indicates relatively small-scale spatial variability, whereas a larger value indicates spatial variability over a larger scale. Data from two points at a distance beyond the range will not be spatially correlated but, rather, will be randomly distributed. The variogram plot exhibits a plateau at this distance.

Prior to variogram analysis, the data were evaluated to determine the existence of linear trends. When an obvious linear trend existed in the variable, spatial data were detrended by fitting a plane surface through each data set (SAS PROC REG), evaluating the surface at each data point, and subtracting the surface from the raw data (19). The variogram then was calculated from the residual values (GS+; Gamma Design Software, Plainwell, MI). For other variables, it was not possible to fit a simple linear trend. In this case, a decreased search neighborhood was utilized to construct variograms by limiting the maximum lag distance used in the analysis. The maximum lag distance is the maximum distance between points used in calculation of the variogram. Both of these procedures were used to account for the apparent nonstationarity present in the experimental site. An underlying assumption of the sample variogram is that of a constant mean with the covariance function dependent only on the distance separating the points, not the direction (12). The presence of a trend in the data would invalidate these assumptions. Simple correlation analysis was performed between rust and soil data on each location as well as the combined data set (combined over all locations) with SAS PROC CORR. Correlation results were considered significant if the probability was significant at $P \leq 0.05$. Multiple regression and multivariate analyses were performed between soil data and rust ratings in an attempt to develop models that could be used to predict rust infestation level (SAS PROC REG and PROC DISCRIM). Finally, maps were constructed by block kriging (Surfer; Golden Software, Golden CO) using the previously determined variograms to determine whether spatial patterns existed within each field.

RESULTS

Soil properties. The soil properties data from all sites displayed significant variability at all locations; however, the most variable properties at each location were different (Table 1). In addition, the overall fertility level at each site also was markedly different and may be related to the observed rust infestation level. At the first site on Golden Ranch Plantation, the most variable properties were soil magnesium, calcium, CEC, potassium, and sulfur, with coefficients of variation (CVs) of 43, 30, 26, 26, and 24%, respectively. The fertility level at this site was medium to very high for phosphorus, low to medium for sulfur and calcium, and very high for potassium and magnesium. In contrast, at the second Golden Ranch location, soil phosphorus was the most variable property, with a CV of 56%, followed by soil calcium, sulfur, magnesium, and potassium, with CVs of 29, 28, 21, and 20%, respectively. The fertility levels of this location were medium to very high for phosphorus, low to optimum for sulfur and calcium, and very high for potassium and magnesium. At Acadia Plantation, soil phosphorus was highly variable, with a CV of 70%. Soil calcium and soil sulfur also showed marked variation, with CV values of 28 and 23%, respectively. The fertility levels at this site were medium to very high for phosphorus, low to medium for sulfur, low to very high for calcium, medium to very high for potassium, and very high for magnesium. At Peltier Farms, the variation in soil properties was much lower, with the exception of soil OM and soil sulfur, with CV values of 30 and 24%, respectively. The fertility levels at this site varied from low to medium for phosphorus and calcium, low for sulfur, medium for potassium, and very high for magnesium. As previously stated, this site had not been in production for several years prior to the plant-cane crop that was rated. Finally, at Rebecca Plantation, significant variability was observed only with soil phosphorus, which had a CV of 37%. The fertility levels at this site varied from optimum to very high for phosphorus, low to medium for sulfur, medium for calcium, and very high for potassium and magnesium.

Spatial variability. The data from soil and rust variogram analysis is summarized in Tables 2 and 3. All soil properties investigated at each location exhibited spatial correlation, with the exception of soil sulfur at the second Golden Ranch location. The spatial dependence was satisfactorily described with isotropic variograms, although a small degree of anisotropy was suggested. Isotropic, or omnidirectional, variograms describe the spatial structure in any direction. Anisotropic variograms, or directional variograms, describe the structure in one direction (10). If significant anisotropy exists in the data, then a series of directional variograms would be necessary. The variogram models that described the individual soil properties varied between locations and between the individual properties investigated, with properties described by exponential, spherical, and linear variograms. For example, the soil properties measured at the first location on Golden Ranch Plantation all were described by spherical variograms with ranges varying from 125 to 190 m (Table 2). However, at the other site on the plantation, it was necessary to include linear variograms to adequately describe some of the soil properties. A similar trend was observed for the sites in Schriever, LA,

TABLE 1. Univariate statistics for soil properties from experiments monitoring variability in sugarcane rust in five fields in southeastern Louisiana, 2005[a]

Statistic[b]	pH	P	K	Ca	Mg	S	OM	CEC
Golden Ranch 1 (*n* = 23, A = 8.9 ha)								
Mean	5.95	36.5	217	2357	539	9.0	1.74	16.8
Minimum	4.9	27	156	1292	264	6.0	1.3	12.0
Maximum	7.0	61	358	4097	1141	14.0	2.3	27.4
Coefficient of variation	9.8	21.4	25.7	30.4	41.8	24.4	16.5	26.0
Golden Ranch 2 (*n* = 27, A = 6.0 ha)								
Mean	6.0	54.3	268	3288	665	11.7	1.93	23.2
Minimum	4.9	23	61	2314	344	7	1.2	16.1
Maximum	7.5	153	367	6420	920	23	2.7	28.8
Coefficient of variation	13.0	55.5	20.2	28.6	21.0	27.6	19.2	12.5
Acadia Plantation (*n* = 53, A = 2.2 ha)								
Mean	6.7	62	223	3106	483	8	1.24	17.8
Minimum	5.0	17	167	1971	339	6	0.9	12.7
Maximum	7.8	234	360	5523	661	15	1.9	27.3
Coefficient of variation	10.1	70.1	17.2	28.0	15.5	22.9	19.1	18.2
Peltier Farms (*n* = 37, A = 0.7 ha)								
Mean	6.1	21	208	2891	710	7	1.3	20.6
Minimum	5.1	14	165	1516	564	5	0.7	17.4
Maximum	7.0	28	242	3317	854	11	2.5	24.0
Coefficient of variation	9.4	16.9	9.2	11.4	10.6	24.3	29.6	9.0
Rebecca Plantation (*n* = 20, A = 4.1 ha)								
Mean	6.5	48	387	4786	1117	11	2.4	31.4
Minimum	5.7	32	284	3877	730	8	1.9	25.7
Maximum	7.4	83	514	6047	1380	16	3.2	36.2
Coefficient of variation	8.3	36.7	14.9	11.5	17.9	15.1	17.9	12.1
All locations combined (*n* = 160)								
Mean	6.3	46	247	3191	656	9	1.6	26.4
Minimum	4.9	14	61	1292	264	5	0.7	12.0
Maximum	7.8	234	514	6422	1380	23	3.2	36.2
Coefficient of variation	11.2	71.6	29.0	30.9	36.6	30.3	32.9	26.4

[a] Univariate statistics for soil pH, Mehlich III-extractable P, K, Ca, Mg, and S (mg kg^{-1} of soil), organic matter (OM%), and cation exchange capacity (CEC, cmol [+] kg^{-1}).
[b] For each location, *n* = total sample number and A = total grid sampled area.

TABLE 2. Semivariance parameters for soil chemical properties and rust estimates from two sugarcane field studies in Gheens, Louisiana, 2005

	Golden Ranch 1				Golden Ranch 2			
Rust rating date or soil property	Ptrt[a]	Mlag (m)[b]	Model[c]	Range (m)	Ptrt[a]	Mlag (m)[b]	Model[c]	Range (m)
18 May	D	298	S	153.9	D	300	L	…
23 May	D	298	L	241.4	D	300	L	…
31 May	D	298	S	116.3	D	300	L	…
6 June	D	298	S	93.5	D	300	L	…
13 June	D	298	S	129.2	ND	300	S	309.3
21 June	D	298	S	113.4	ND	…	NC	…
27 June	D	298	S	123.8	ND	200	E	270.9
Soil pH	D	298	S	159.0	ND	300	S	201.3
Phosphorus (mg kg^{-1})	ND	298	S	190.1	D	300	L	…
Potassium (mg kg^{-1})	D	298	S	132.2	ND	200	S	96.7
Calcium (mg kg^{-1})	D	298	S	132.3	ND	300	S	184.1
Magnesium (mg kg^{-1})	D	298	S	139.5	D	300	L	…
Sulfur (mg kg^{-1})	D	298	S	178.6	D	300	NC	…
Organic matter (%)	ND	298	S	140.9	ND	300	S	267.0
Cation exchange capacity (meq 100 g^{-1})	D	298	S	125.1	D	300	L	…

[a] Data set pretreatment: D = data set detrended by fitting plane surface, subtracting trend, and performing variogram analysis on residuals; and ND = not detrended.
[b] Maximum lag distance used in variogram fitting.
[c] Proposed variogram model: E = exponential, S = spherical, L = linear, and NC = not spatially correlated.

with spherical variograms describing the data at Acadia Plantation but exponential and linear variograms required at the other two sites (Table 3). Although it is possible to estimate the range with exponential variograms, an estimate is not possible with linear variograms. Linear variograms do not possess a sill in the variogram and indicate that the spatial correlation extends beyond the greatest distance between points in the data set. The sill is the point on the experimental variogram at which the semivariance reaches a plateau. At this point, the samples are no longer spatially correlated and the value of the semivariance is directly proportional to the sample variance.

At the first site on Golden Ranch Plantation, all soil properties and rust ratings were spatially correlated, and the majority was described by spherical variograms, with the exception of the

TABLE 3. Semivariance parameters for soil chemical properties and rust estimates from three sugarcane field studies in Schriever, Louisiana, 2005

	Acadia Plantation				Peltier Farms				Rebecca Plantation			
Rust, soil[a]	Ptrt[b]	Mlag (m)[c]	Model[d]	Range (m)	Ptrt[b]	Mlag (m)[c]	Model[d]	Range (m)	Ptrt[b]	Mlag (m)[c]	Model[d]	Range (m)
19 May	…	…	…	…	…	…	…	…	ND	190	S	167.1
23/24 May	D	160	S	104.5	D	80	S	34.6	ND	190	S	255.5
1 June	D	160	S	142.3	D	80	S	41.9	ND	180	S	88.6
6 June	D	160	S	112.2	D	60	S	27.0	ND	180	S	119.1
13 June,	ND	160	S	74.4	D	80	S	69.5	ND	180	S	172.4
21 June	ND	125	S	68.1	ND	80	S	35.6	ND	180	S	85.1
27 June	ND	125	S	29.0	ND	80	S	25.5	ND	150	S	82.5
Soil pH	D	160	S	88.0	ND	80	S	66.4	ND	180	S	121.2
P (mg kg^{-1})	ND	160	S	64.9	ND	80	S	60.4	D	180	S	123.2
K (mg kg^{-1})	D	160	S	85.2	ND	70	S	46.6	ND	180	S	85.5
Ca (mg kg^{-1})	D	160	S	90.9	ND	80	L	…	ND	190	S	134.5
Mg (mg kg^{-1})	ND	160	S	41.6	ND	80	S	61.2	D	…	L	…
S (mg kg^{-1})	ND	120	S	42.2	ND	80	S	70.9	D	…	L	…
OM (%)	D	180	S	120.9	ND	80	S	49.4	ND	190	E	92.7
CEC (meq 100 g^{-1})	ND	160	S	39.3	ND	80	S	50.0	D	…	L	…

[a] Rust rating date or soil property. OM = organic matter and CEC = cation exchange capacity.

[b] Data set pretreatment: D = data set detrended by fitting plane surface, subtracting trend, and performing variogram analysis on residuals; and ND = not detrended.

[c] Maximum lag distance used in variogram fitting.

[d] Proposed variogram model: E = exponential and S = spherical.

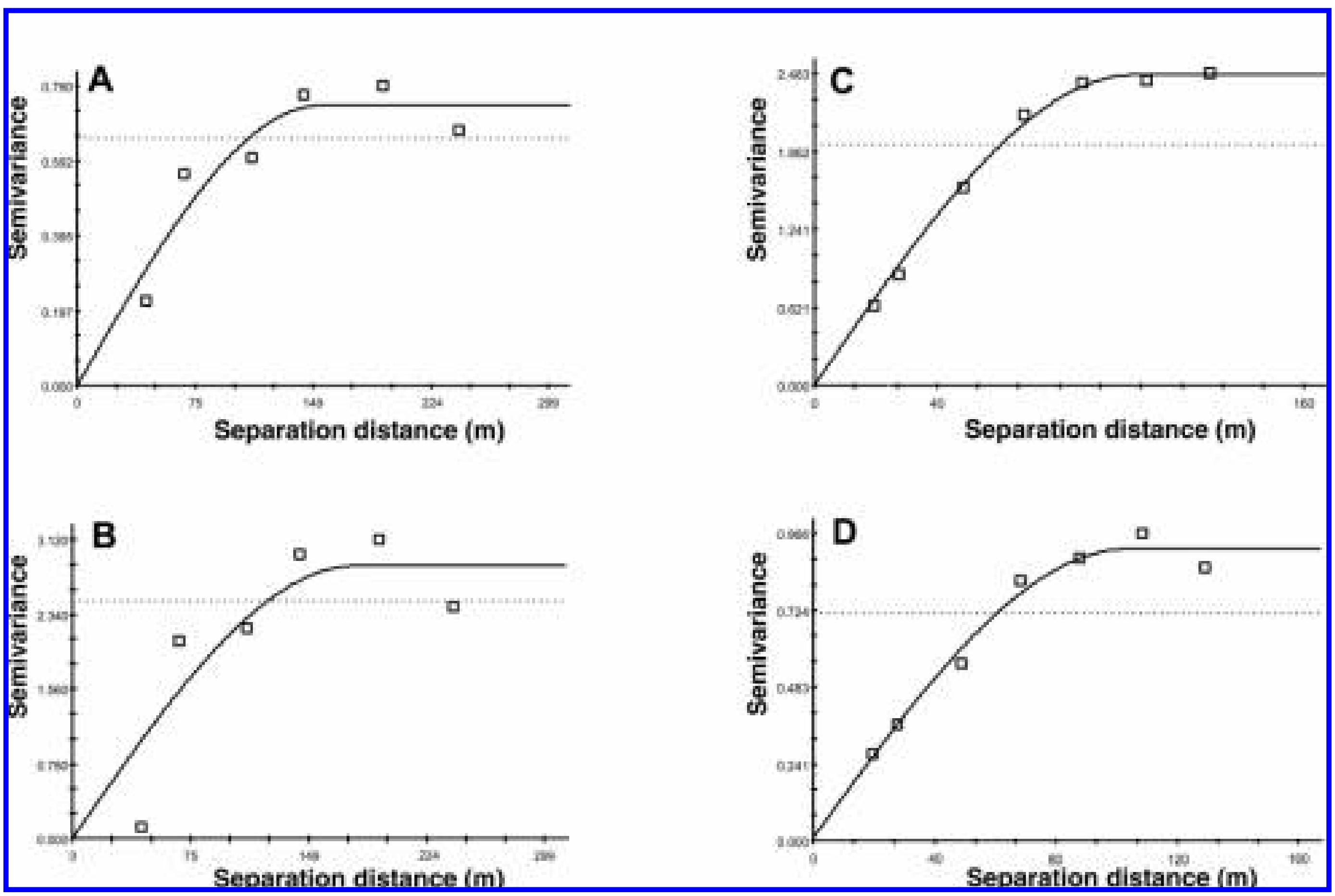

Fig. 1. Isotropic variograms for **A,** first rust rating on 18 May 2005 at Golden Ranch Plantation Site 1; **B,** soil sulfur at Golden Ranch Plantation Site 1; **C,** first rust rating on 23 May 2005 Acadia Plantation; and **D,** soil pH Acadia Plantation.

second rust rating (23 May 2005), which was described by a linear variogram (Table 2). The range of spatial correlation varied from 94 to 241 m for the rust ratings and from 125 to 190 m for soil properties. The spherical variograms used to describe the initial rust rating and soil sulfur for this location are shown in Figure 1A and B, respectively. The close agreement in variogram structure and range between these two parameters would suggest that soil sulfur could serve as a spatial predictor for rust infestation level. The possible use of co-kriging to predict rust infestation levels from soil properties will be investigated in future research. At the second location on Golden Ranch Plantation, the majority of rust ratings and soil properties also were spatially correlated, with the exception of soil sulfur and the sixth rust rating (21 June 2005) (Table 2). In contrast to the first site, it was necessary to utilize linear and exponential variograms, in addition to spherical variograms, to model the spatial variability. The range of correlation also was significantly greater and varied from 271 to 309 m for rust ratings and from 97 to 267 m for soil properties (Table 2). As previously stated, it was not possible to estimate the range for the ratings and soil properties that were modeled with linear variograms. The range of spatial correlation for these cases extended beyond the test boundaries.

All properties measured at the three locations in Schriever, LA were spatially correlated (Table 3). There also was an overall tendency for the range of spatial correlation to be lower for both rust ratings and soil properties at these sites. This is not surprising because, as previously mentioned, the studies at Acadia Plantation and Peltier Farms both were mapped on finer mesh grids to determine whether spatial structure existed at smaller scales. At Acadia Plantation, the spherical variogram was used to describe all measured parameters, with the range varying from 29 to 142 m for rust ratings and from 39 to 121 m for soil properties. The spherical variograms for the initial rust infestation level and soil pH at this location are shown in Figure 1C and D, respectively. The close agreement in variogram structures and ranges suggests that soil pH also would be a useful spatial predictor for rust infestation level. At Peltier Farms, the range of spatial correlation was markedly lower for both rust ratings and soil properties, with soil properties varying from 47 to 71 m and rust ratings from 26 to 70 m. This most probably is related to the short time this field has been in production and possibly lower levels of rust inoculum. Spherical variograms described all parameters, with the exception of soil calcium, in which a linear variogram best described the data. Finally, at Rebecca Plantation, the average range was somewhat greater than the other sites in Schriever, but still tended to be less than the sites in Gheens. Rust ratings varied from 83 to 256 m and soil properties from 86 to 135 m. Spherical variograms described all rust ratings, whereas soil properties required spherical, exponential, and linear variograms to model the spatial variability.

Relationships between soil properties and rust variability. *Correlation analysis.* Soil samples were taken at the same time that initial rust ratings were made. It was anticipated that the strongest correlations between the variability of rust ratings and soil properties within fields would be for the initial ratings. Correlations with the later ratings may offer some insight into disease progression. To investigate this possibility, results of the correlation analysis between rust and soil parameters are presented for the initial rating, one intermediary rating, and the final rating. At the first location on Golden Ranch Plantation, there were a number of significant correlations between rust rating 1 (19 May) and soil parameters (Table 4), including soil pH, calcium, magnesium, and sulfur ($r = -0.62^{**}$, -0.56^{**}, -0.51^{*}, and 0.68^{***}). These properties remained significantly correlated throughout all ratings, with the exception of soil sulfur at the last rating. In addition, at later ratings, soil potassium, OM, and CEC displayed significant correlations with rust severity. At the second location at Golden Ranch, there were fewer significant correlations overall; however, soil phosphorus, magnesium, and sulfur were correlated with initial rust ratings ($r = 0.41^{**}$, -0.49^{***}, and 0.45^{**}) (Table 4). Soil magnesium and sulfur remained correlated to intermediary ratings but were not significant at the final rating period where, instead, soil pH, calcium, and OM were significant.

At the sites in Schriever, significant correlations between rust levels and soil properties were observed at Acadia and Rebecca Plantations but not at the Peltier Farms site (Table 4). At Acadia Plantation, soil pH, phosphorus, potassium, and calcium displayed significant correlations on the initial rating period ($r = 0.42^{**}$, 0.44^{**}, 0.39^{**}, and 0.34^{**}). The same properties were even

TABLE 4. Simple (Pearson's) correlation coefficients between soil properties and sugarcane rust ratings from five fields in southern Louisiana, 2005

Rust rating date	pH	P	K	Ca	Mg	S	OM[a]	CEC[a]
Golden Ranch 1								
18 May	-0.62^{**}[a]	ns[a]	ns	-0.56^{**}	-0.51^{*}[a]	0.68^{***}[a]	ns	ns
6 June	-0.53^{**}	ns	-0.57^{**}	-0.64^{***}	-0.72^{***}	0.45^{*}	ns	-0.69^{***}
27 June	-0.51^{*}	ns	-0.48^{**}	-0.42^{*}	-0.53^{**}	ns	-0.45^{*}	-0.50^{*}
Golden Ranch 2								
18 May	ns	0.41^{*}	ns	ns	-0.49^{***}	0.45^{*}	ns	ns
6 June	ns	ns	ns	ns	-0.48^{**}	0.49^{**}	ns	ns
27 June	-0.58^{**}	ns	ns	-0.49^{**}	ns	ns	0.38^{*}	ns
Acadia Plantation 1								
23 May	0.42^{**}	0.44^{**}	0.39^{**}	0.34^{*}	ns	ns	ns	ns
13 June	0.57^{***}	0.45^{**}	0.45^{**}	0.44^{**}	ns	0.36^{**}	ns	ns
27 June	ns	ns	ns	ns	ns	ns	ns	ns
Peltier Farms								
23 May	ns	ns	ns	ns	ns	ns	ns	ns
13 June	ns	ns	ns	ns	ns	ns	ns	ns
27 June	ns	ns	ns	ns	ns	ns	ns	ns
Rebecca Plantation								
19 May	0.48^{*}	0.81^{***}	ns	ns	-0.52^{*}	0.63^{**}	0.57^{**}	ns
6 June	ns	ns	ns	ns	ns	ns	0.50^{*}	ns
27 June	ns	ns	ns	ns	ns	ns	ns	ns
All locations combined								
18/19 May	ns	0.30^{***}	ns	ns	ns	0.45^{***}	0.19^{*}	ns
6/13 June	0.18^{*}	0.16^{*}	-0.29^{***}	ns	-0.27^{***}	ns	-0.40^{***}	-0.18^{*}
27 June	ns	ns	-0.17^{*}	ns	ns	ns	-0.26^{**}	ns

[a] OM = organic matter; CEC = cation exchange capacity; *, **, and *** indicate significance at the 0.05, 0.01, and 0.001 probability levels, respectively; and ns = not significant.

more positively correlated for the intermediary ratings (r = 0.57***, 0.45**, 0.45**, and 0.44**), and soil sulfur also was correlated (r = 0.36**) (Table 4). No soil properties were correlated with rust ratings on the final rating date. Finally, at Rebecca Plantation, there were several soil properties correlated with rust severity, including soil pH, phosphorus, magnesium, sulfur, and OM (r = 0.48*, 0.81***, –0.52*, 0.63**, and 0.57**) (Table 4). Only soil OM was correlated at the intermediary rating (r = 0.50*), and no soil properties were correlated at the final rating. When all locations were combined, soil sulfur, phosphorus, and OM were correlated with rust severity at the initial rating (r = 0.45***, 0.30***, and 0.19*) (Table 4). At the intermediary rating, soil potassium, magnesium, and soil OM were most strongly correlated and, at the final rating, soil OM best described rust levels.

Multiple regression. Regression analysis was performed between soil parameters and rust severity ratings in an attempt to develop equations that could be used to identify sugarcane fields that would have an increased susceptibility to rust infection. Models were developed for the first rust rating at each location and for the combined data set (Table 5). Models were selected based on their overall fit of the data as estimated by the coefficient of multiple determination (R^2), and simplicity (i.e., fewer parameters) as determined by the Mallow's Cp statistic. Thus, the best model was indicated by a higher R^2 value and a lower Cp statistic (20). The Cp statistic is a measure of the total squared error for a particular model, which includes both the error variance and the bias introduced by not including important variables in the model. For an unbiased model, Cp will be equal to the total parameters in the model (including the constant term). Under- or overfitted models will have a larger Cp value from an increased bias or error variance, respectively. At the first site on Golden Ranch Plantation, two models were developed to describe rust severity. The first model used soil sulfur alone (R^2 = 0.46***), whereas the second model added soil calcium to improve the overall data description (R^2 = 0.56***) (Table 5). Sulfur had positive influence on rust severity in both models, whereas calcium had a negative effect in the two parameter model. The two-parameter model was selected as the most appropriate, unbiased model (Cp = 3.0). At the second site on Golden Ranch, a single model was developed that included soil phosphorus, calcium, and OM (R^2 = 0.44***, Cp = 4.0). Phosphorus had a positive influence on rust severity and calcium, and OM had a negative influence.

All of the models that were developed for the sites in Schriever included soil phosphorus and were positively associated with rust severity. At the site on Acadia Plantation, a single model was developed that included soil pH, phosphorus, potassium, and calcium (R^2 = 0.28**, Cp = 5.0). On Peltier Farms, a model was developed that included soil phosphorus, potassium, magnesium, and OM (R^2 = 0.38**, Cp = 5.0) (Table 5). Finally, on Rebecca Plantation, two models were selected, one with only soil phosphorus (R^2 = 0.65***, Cp = 5.7) and a second that added soil OM (R^2 = 0.73***, Cp = 3.0). When all locations were combined, a significant model was selected that included soil sulfur and phosphorus (R^2 = 0.22***, Cp = 3.0) (Table 5). Both soil sulfur and phosphorus had a positive influence on rust severity. It is clear from examination of the combined model and the previously described correlation data (Table 4) that soil sulfur and soil phosphorus appear to have a significant link with sugarcane rust severity. Soil OM, potassium, and calcium also appear to have an influence on severity, although these effects may be more location specific.

Discriminant analysis. Discriminant analysis was employed in an attempt to improve the description of rust severity from soil properties data for the combined data set. In this analysis, two strategies were employed. In the first, discriminant analysis was used to predict each level of the first rust rating for the combined data set, where the rating varied from 1 to 7. In the second, the rust ratings were condensed into low, medium, and high severity levels, where low varied from 1 to 2, medium from 3 to 5, and high from 6 to 7. Linear discriminant functions then were developed for each scenario. In the first case, an overall discrimination percentage of 56% correct classifications was achieved (Table 6). When the ratings were grouped, the discrimination percentage increased to 77% correct classifications (Table 6).

Soil and rust contour maps. Selected soil and rust severity maps are presented in Figure 2. An examination of Figure 2A and B suggests that a relation exists between soil rust severity and soil sulfur at the first site on Golden Ranch Plantation. The rust levels are clearly higher on the northern edge of Figure 2A and correspond directly with higher sulfur levels in the same area (Fig. 2B). In addition, lower sulfur levels also are associated with lower rust incidence on the eastern and southeastern portions of Figure 2A and B. In a similar fashion, the relationship between soil pH and rust severity is demonstrated in Figure 2C and D. Higher rust levels are clearly present on the western edge of Figure 2C, and this corresponds with higher pH levels in the same area. Lower rust levels on the southern portion of Figure 2C are associated with lower pH areas in that section.

DISCUSSION

Significant variability was observed in soil properties from the five locations, with the CVs ranging from 9 to 70%. Soil phosphorus exhibited the greatest degree of variability and soil pH the least. The overall fertility levels of each location also were quite variable. The second site at Golden Ranch Plantation had the highest fertility levels, with all soil nutrients reaching optimum or

TABLE 5. Regression models to predict initial sugarcane rust ratings from soil properties from five fields in southern Louisiana, 2005

Regression model	Statistic	
	R^2	Cp
Golden Ranch 1 (R1 = 18 May)		
R1 = –0.96 + 0.37*Sulfur	0.46***	5.65
R1 = 1.06 – 0.0006*calcium + 0.30*sulfur	0.56***	3.00
Golden Ranch 2 (R1 = 18 May)		
R1 = 9.90 + 0.1*phosphorus – 0.002*calcium – 2.31*organic matter (OM)	0.44**	4.00
Acadia Plantation (R1 = 23 May)		
R1 = –3.26 + 0.62*pH + 0.009*phosphorus + 0.12*potassium – 0.0007*calcium	0.28**	5.00
Peltier Farms (R1 = 24 May)		
R1 = 4.17 + 0.06*phosphorus + 0.01*potassium – 0.006*magnesium – 1.22*OM	0.38**	5.00
Rebecca Plantation (R1 = 19 May)		
R1 = –0.91 + 0.67*phosphorus	0.65***	5.70
R1 = –2.47 + 0.06*phosphorus + 0.85*OM	0.73***	3.00
All locations combined		
R1 = 0.31 + 0.20*sulfur + 0.005*phosphorus	0.22***	3.00

TABLE 6. Linear discriminant functions to predict initial sugarcane rust ratings from soil properties from five fields in southern Louisiana, 2005

	Model coefficients									
	Numerical rust severity rating[a]							Rust rating range[b]		
Variable[c]	1	2	3	4	5	6	7	L	M	H
Constant	–488.9	–495.7	–493.8	–492.6	–494.1	–599.7	–484.6	–490.3	–492.6	–498.4
pH	155.3	156.2	155.9	154.4	155.5	165.0	150.9	154.8	154.6	152.8
Phosphorus	–0.54	–0.53	–0.49	–0.61	–0.52	–0.24	–0.54	–0.63	–0.65	–0.59
Potassium	–0.06	–0.07	–0.08	–0.02	–0.04	–0.42	–0.13	0.02	0.5	–0.1
Calcium	–0.15	–0.15	–0.15	–0.15	–0.15	–0.16	–0.14	–0.15	–0.15	–0.14
Magnesium	–0.23	–0.23	–0.23	–0.25	–0.24	–0.19	–0.21	–0.2	–0.26	–0.22
Sulfur	2.1	2.2	2.3	2.76	2.3	2.97	4.6	2.6	2.77	4.6
Organic matter	20.4	20.5	20.7	20.9	21.1	30.0	17.05	17.1	17.9	16.3
CEC	30.0	30.2	30.0	29.8	31.1	33.4	28.5	29.2	29.3	28.6
Correct (%)	47.7	41.9	33.3	60.0	46.2	100.0	66.7	75.0	84.6	75.2
Sample size (*n*)	21	26	10	3	6	1	2	115	13	3

[a] Numerical rust severity rating from 0 to 9, where 0= no rust.
[b] Grouped numerical ratings where, L = 1 and 2; M = 3, 4, and 5; and H = 6 and 7.
[c] CEC = cation exchange capacity.
[d] Percentage of observations correctly classified.

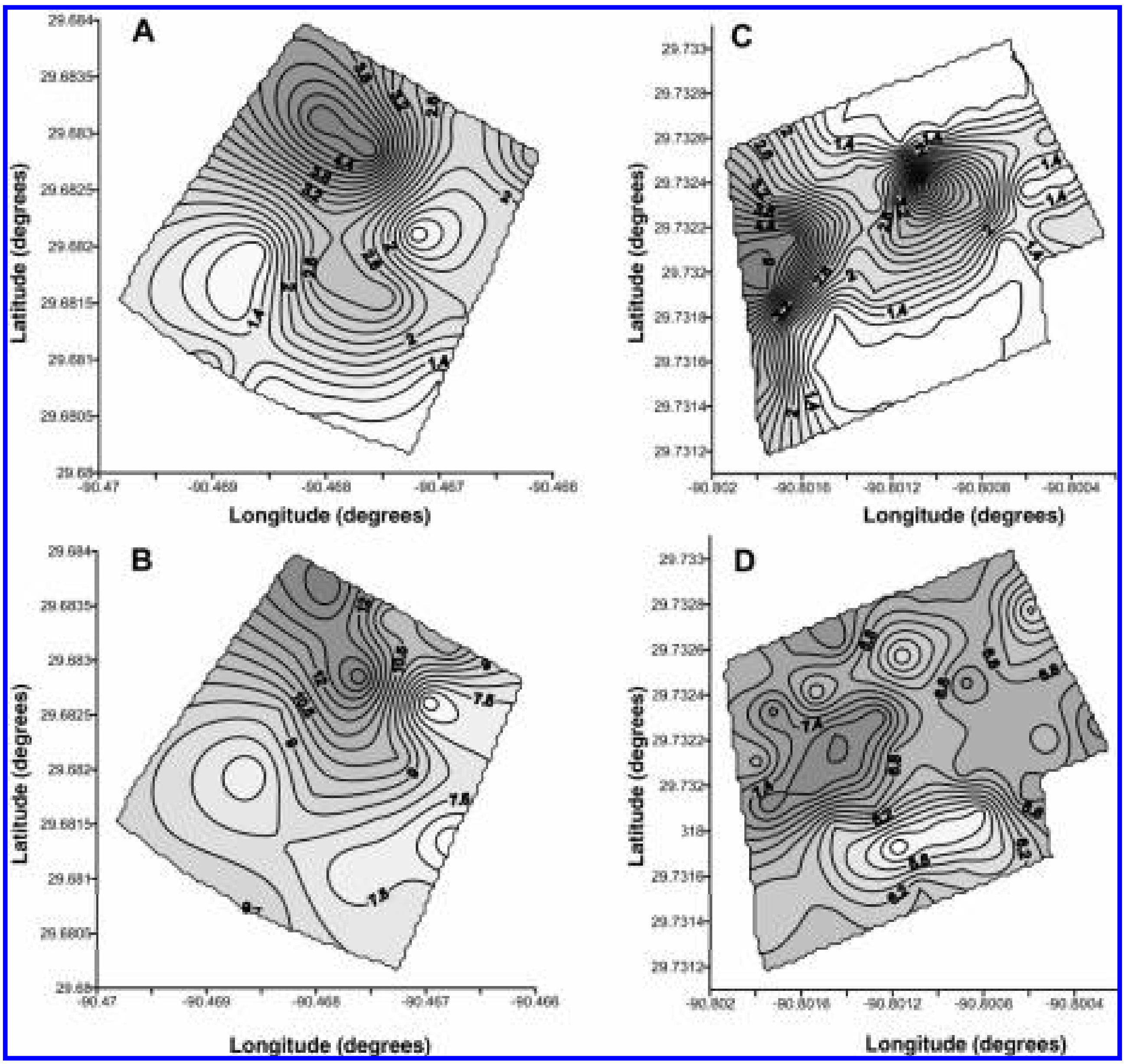

Fig. 2. Contour plots for **A,** first rust rating on 18 May 2005 at Golden Ranch Plantation Site 1; **B,** soil sulfur at Golden Ranch Plantation Site 1; **C,** first rust rating on 23 May 2005 at Acadia Plantation; and **D,** soil pH at Acadia Plantation.

very high levels at sampling points. In contrast, the site at Peltier Farms had many points where soil nutrients were in the low to medium ranges, and this was the only field in which no soil properties correlated with rust ratings. This probably is due to the field's time out of production, when soil nutrient levels declined. Areas in which nutrients were present at optimum or very high levels frequently were associated with higher rust levels.

In addition to the observed variability, rust ratings were found to be spatially correlated in 32 of 33 site–rating date combinations. The fact that all but two of the rust and soil parameters measured in this study were spatially correlated is significant. The spatial dependence of the measured soil properties has been described in other Louisiana sugarcane fields (11); however, to the authors' knowledge, this spatial dependence has not been associated with sugarcane rust. This spatial dependence would indicate that the distribution of rust within the study sites is not random but, rather, is dependent on location. This spatial dependence also can be modeled successfully through the use of variograms. Another important observation is that the range of spatial correlation is similar for the measured soil properties and rust ratings, suggesting a possible link between the two parameters. Soil properties also were spatially correlated at all locations, with the exception of soil sulfur at one location on Golden Ranch Plantation. The range of spatial correlation varied from 29 to 241 m for rust ratings and from 39 to 201 m for soil properties. The fact that the range of spatial correlation is similar for the measured soil properties and rust ratings suggests a possible link between the two parameters.

Several interesting trends become apparent when the correlation data from each location is examined. First, soil phosphorus was always positively correlated with rust levels. In addition, there appeared to be a threshold field mean value that had to be achieved before phosphorus levels could be associated with rust severity (>27 mg kg^{-1}). This is just slightly below the optimum fertility level which occurs at ≈30 mg kg^{-1}. A similar trend was observed for soil sulfur, which also was positively correlated with rust levels and had an apparent threshold of 7 mg kg^{-1}. This value is significantly less the optimum level of 20 mg kg^{-1}. Soil OM was not consistently correlated (positively or negatively) with rust levels, but had an apparent threshold value of 1.3%, and soil magnesium was always negatively correlated with rust levels. Finally, soil pH appeared to be negatively correlated with rust levels when the mean soil pH was ≤6.0 and positively correlated when the pH was >6.0. In addition, the strength of the association appeared to increase with increasing pH. These trends, taken together, appear to suggest that, as fertility levels increase, the severity of rust infections also increases. A similar relation between sugarcane rust incidence and soil properties was reported in Florida (3). The authors reported that rust was positively associated with water-extractable phosphorus levels and negatively correlated with soil pH. Soil calcium, potassium, and magnesium were associated with rust severity, but not in a consistent manner. The apparent association between excess nutrient levels and rust severity may be related to the effects that these same conditions have on plant growth and, ultimately, on yield. High-nutrient conditions will be associated with vigorous plant growth and most likely will result in a denser canopy that closes over more rapidly. This would create an environment more suitable to rust development.

Multiple regression analysis further highlighted the relation between rust severity, soil phosphorus, and sulfur. Soil OM, potassium, and calcium also appear to have an influence on severity, although these effects may be more location specific. Rust severity could be predicted using linear discriminant functions with an accuracy of 77%, provided that the severity was expressed as low, medium, and high infestation levels. Finally, contour plots of soil properties and rust ratings clearly show the direct and spatial relation between soil fertility and rust severity. These combined data suggest that sugarcane growers that apply fertilizer in excess of plant requirements will increase the incidence and severity of rust infestations in their fields.

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